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DARK MATTER AND COSMOLOGY *

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Abstract

The cosmological dark matter problem is reviewed. The Big Bang Nucleosynthesis constraints on the baryon density are compared with the densities implied by visible matter, dark halos, dynamics of clusters, gravitational lenses, large-scale velocity flows, and the $\Omega = 1$ flatness/inflation argument. It is shown that (1) the majority of baryons are dark; and (2) non-baryonic dark matter is probably required on large scales. It is also noted that halo dark matter could be either baryonic or non-baryonic. Descrimination between "cold" and "hot" non-baryonic candidates is shown to depend on the assumed "seeds" that stimulate structure formation. Gaussian density fluctuations, such as those induced by quantum fluctuations, favor cold dark matter, whereas topological defects such as strings, textures or domain walls may work equally or better with hot dark matter. A possible connection between cold dark matter, globular cluster ages and the Hubble constant is mentioned. Recent large-scale structure measurements, coupled with microwave anisotropy limits, are shown to raise some questions for the previously favored density fluctuation picture. Accelerator and underground limits on dark matter candidates are also reviewed.

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INTRODUCTION

The cosmological dark matter problem has become one of the most exciting and active areas of modern scientific study. This review paper will attempt to summarize the multifaceted nature of the problem.

The lack of success so far in the dark matter searches and the related structure formation problem have led some journlists to question the Big Bang itself. Hopefully, our recent paper[1] has shown that such a conclusion is fallacious. In fact, the basic Big Bang model is in remarkable good shape due to recent new observations and experiments showing that we understand the universe when it was very hot and very dense and had an age of about 1 second. Galaxy formation and the related dark matter problems are probably probing the universe at ages of 10^6 to 10^9 years and thus are not probing the Big Bang itself. Thus, before discussing the problems and recent observations regarding large-scale structure, galaxy formation and dark matter, this article will first review how observations and experiments[1] have now established the basic hot Big Bang universe to a remarkable level of confidence so that any reasonable model for structure formation must operate in the Big Bang framework.

After briefly reviewing the basic Big Bang arguments, we will then discuss the generic features that any structure formation model must have: (1) matter, and (2) seeds to clump the matter. We will see that the bulk of the matter is dark (non-shining) and that some of the dark matter must be just non-shining ordinary matter in, say, brown dwarfs or some other low luminosity form, but the bulk of the dark matter is probably in some new exotic form such as low-mass neutrinos, "axions," or supersymmetric "neutralinos." We will also see that the "seeds" can be either small, random density fluctuations or they could also be something more exotic like cosmic "strings," "walls," or "textures." The discussion here will follow other recent reviews.[2]

Observations and experiments are beginning to test the various combinations of matter and seeds. In particular, different combinations predict different patterns for the resultant structure and different levels and distributions for residual fluctuations in the cosmic microwave background radiation. We will examine where the current situation lies, what combinations are eliminated and which still look promising.

THE ESTABLISHMENT OF THE HOT BIG BANG

While Hubble's work in the 1920's established an expanding universe, the establishment of modern physical cosmology and the hot Big Bang naturally focuses on two key quantitative observational tests:

(1) the cosmic microwave background radiation (CBR); and

(2) Big Bang Nucleosynthesis (BBN) and the light element abundances.

The magnificent agreement of the 1990 COBE satellite measurements[3] with a perfect 2.735K blackbody radiation spectrum has been well discussed.[1] We should remember that this spectral shape is exactly what the hot Big Bang predicts and no other theory naturally yields such a precise black body shape with only one free parameter, T, the temperature. A second precision test of the standard model is the consistency of light element abundance measurements[4] and also the recent accelerator measurements[5] of the number of neutrino species with the predictions of nucleosynthesis calculations in the Big Bang model.[6,4]

Figure 1 shows the abundances produced in the standard calculation as a function of the fraction of the critical density. The vertical band in Figure 1 is the allowed values that are simultaneously consistent with the observed light element abundances of ^{4}He, ^{2}H, ^{3}He and ^{7}Li extrapolated to their primordial values unassociated with any heavier elements. Since ^{2}H cannot be produced significantly in any non-cosmological process,[7] only destroyed. the present abundance of ^{2}H puts an upper limit on the baryon density. Conversely, ^{3}He is made in stars, and since the bulk of the excess cosmological ^{2}H over the present value burns to ^{3}He in stars, the sum of ^{2}H plus ^{3}He provides a lower bound on the baryon density. The allowed range of baryon density that is consistent with these bounds requires ^{7}Li to be at the minimum in its production curve (as shown in Figure 1). The measurements of the Spites,[8] subsequently verified by others, giving $^7\mathrm{Li/H} \sim 10^{-10}$ in the primitive (Pop II) stars, further substantiates these arguments. Thus, the light elements with abundances ranging from $\sim$ 24% to one part in 10^{10} all fit with the cosmological predictions, with the one adjustable parameter giving baryon density $\Omega_b \simeq 0.05$.

BIG BANG NUCLEOSYNTHESIS

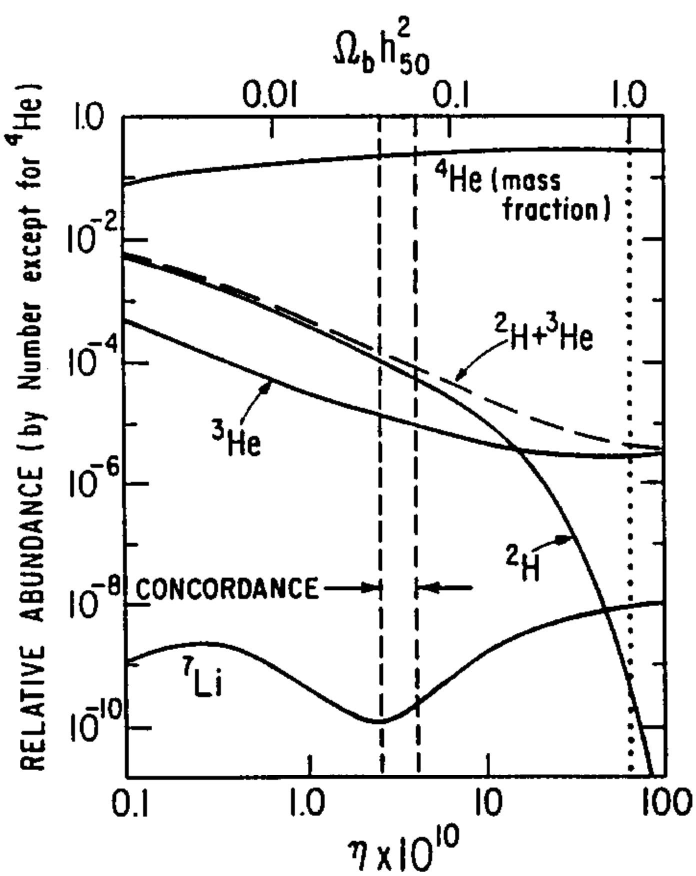

Figure 1. Standard Big Bang Nucleosynthesis yields from recent recalculation by Olive, Schramm, Steigman and Walker.[4]

Recent attempts to find alternatives to this conclusion by introducing variations in the assumptions have ended up[9] (once the models are treated in detail) reaching essentially the same constraint on Ω_b as in the standard model. Thus, the conclusions have proven remarkably robust.

Added to the impressive agreement of the abundances has been the measurement[5] using high energy colliders of the number of neutrino families, $N_\nu = 2.99 \pm 0.05$. Nucleosynthesis arguments, developed in the 1970s by Steigman, Schramm and Gunn,[6] show that the cosmological ^{4}He abundance is quantitatively related to N_ν. The current parameter values[10,4] yield the cosmological prediction $N_\nu \lesssim 3.3$, specifically ruling out any light neutrinos beyond e, μ and τ, and consistent with the collider measurements. This experimental particle physics test of the cosmological model is a "first" and effectively "consummates the marriage"[1] of particle physics and cosmology. It also gives us even further confidence that we understand cosmological nucleosynthesis and thus know the cosmological baryon density as well as giving us confidence in the basic hot Big Bang model of the universe.

DARK MATTER REQUIREMENTS

The narrow range in baryon density for which concordance occurs is very interesting. Note that the constraint on Ω_b means that the universe *cannot be closed with normal matter*. If the universe is truly at its critical density, then nonbaryonic matter is required.

The arguments requiring some sort of dark matter fall into separate and possibly distinct areas. (For a complete discussion of the dark matter problems, see reference 11.) The visible matter in the universe (stars) yields a fraction of the critical density of only about 0.007. This can be compared to the implied densities using Newtonian mechanics applied to various astronomical systems. These arguments are summarized in Figure 2 (adapted from reference 2). It should be noted that these arguments (flat rotation curves, dynamics of binary galaxies, etc.) reliably demonstrate that galactic halos seem to have a mass ~ 10 times the visible mass.

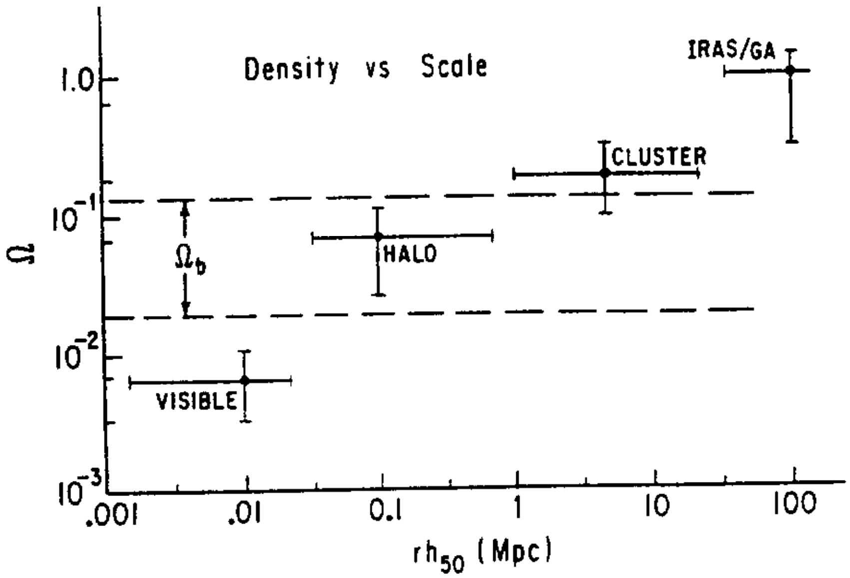

Figure 2. Implied densities versus the scale of the measurements.

Note, however, that Big Bang nucleosynthesis requires that the bulk of the baryons in the universe be dark since $\Omega_{vis} \ll \Omega_b$ and $\Omega_b \sim \Omega_{halo}$. Thus, the dark halos could, in principle, be baryonic (and if they are not, there is an interesting coincidence[12] between Ω_b and Ω_{halo}). However, when similar dynamical arguments are applied to larger systems such as clusters of galaxies, the implied Ω rises to about 0.2. This same value of Ω can also be obtained from gravitational lensing of distant quasars and galaxies by intervening clusters of galaxies. While the uncertainties might marginally allow an overlap between Ω_b and $\Omega_{cluster}$ at ~ 0.1, the central values are already hinting that, on the scales of clusters of galaxies (about 1 to 10 Mpc), there appears to be more than baryonic matter.

A new and very dramatic development on even larger scales than clusters now suggests that on even larger scales (50 to 100 Mpc), the density approaches the critical value ($\Omega \sim 1$).[13,14,15] This new development utilizes the combined velocity and distance estimates for galaxies out to and slightly beyond the so-called "Great Attractor." The Great Attractor was discovered by a group of astronomers who called themselves the Seven Samurai.[16,17,18] This team determined the so-called peculiar velocities for galaxies out to about 100 Mpc. They did this by estimating the distance and using this to determine the cosmological expansion velocity. The difference between the galaxy's actual velocity as determined by the redshift and the inferred expansion velocity is the "peculiar velocity." From analyzing these peculiar velocities, it became apparent that there was a large flow of galaxies (including our local group) towards something they called the Great Attractor. Recently this flow has been mapped out in much greater detail using redshifts measured for the catalogue of galaxies found by the Infrared Astronomy Satellite (IRAS). This data has been analyzed by teams from MIT, Israel, Toronto, England, Stony Brook, Berkeley and Fermilab, and the conclusion to date is that the observed dynamics on this scale require $\Omega \sim 1 \pm 0.6$. While the uncertainties are still large and systematic errors cannot be ruled out, it nonetheless does hint that Ω exceeds Ω_b on large scales.

Of course, theoretical cosmologists have long assumed that Ω is unity, so these recent, preliminary results may prove to be a confirmation of this theoretical assumption. The theoretical argument is essentially that the only long-lived natural value for Ω is unity, and that inflation or something like it provided the early universe with the mechanism to achieve that value and thereby solve the so-called flatness and smoothness problems.

Before turning to exotic non-baryonic matter, we should note that some baryonic dark matter must exist since the lower bound from Big Bang nucleosynthesis is greater than the upper limits on the amount of visible matter in the universe. We do not know what form this baryonic dark matter is in. It could be either in condensed objects in the halo, such as brown dwarfs and jupiters (objects with $\lesssim 0.08 M_\odot$ so they are not bright shining stars), or in black holes (which at the time of nucleosynthesis would have been baryons). Or, if the baryonic dark matter is not in the halo, it could be in hot intergalactic gas, hot enough not to show absorption lines, but not so hot as to be seen in x-rays. Evidence for some hot gas is found in clusters of galaxies. However, the amount of gas in clusters would not be enough to make up the entire missing baryonic matter. Another possible hiding place for the dark baryons would be failed galaxies, large clumps of baryons that condense gravitationally but did not produce stars.

The more exotic non-baryonic dark matter can be divided into two major categories for cosmological purposes: hot dark matter (HDM) and cold dark matter (CDM). Hot dark matter is matter that is moving near the speed of light until just before the epoch of galaxy formation, the best example being low mass neutrinos with $m_\nu c^2 \sim 25eV$. Cold dark matter is matter that is moving slowly at the epoch of galaxy formation. Because it is moving slowly, it can clump on very small scales, whereas HDM tends to have more difficulty in being confined on small scales. Examples of CDM could be massive neutrino-like particles with masses greater than several times the mass of a proton or the lightest supersymmetric particle which is presumed to be stable and might also have a mass of several GeV. Following Michael Turner, all such Weakly Interacting Massive Particles are called "WIMPS" and, in the case of the supersymmetric candidates, they are the "neutralinos" or "INOS" for short. Axions are very light but would also be moving very slowly and, thus, would clump on small scales. Or, for CDM, there are non-elementary particle candidates, such as planetary mass blackholes or "nuggets" of strange quark matter.[18] Note that CDM would clump in halos, thus requiring the dark baryonic matter to be out between galaxies, whereas HDM would allow baryonic halos. Table 1 summarizes the various dark matter candidates, both baryonic and non-baryonic and Figure 3 shows the relationship between Ω and mass.

Table 1

MATTER

Baryonic ($\Omega_b \sim 0.05$)

- VISIBLE $\Omega_{vis} \lesssim 0.01$
- DARK
  - Halo
    - Jupiters
    - Brown Dwarfs
    - Stellar Black Holes
  - Intergalactic
    - Hot gas at $T \sim 10^5 K$
    - Stillborn Galaxies

Non Baryonic ($\Omega_{nb} \sim 0.95$)

- HOT
  - $m_{\nu_\tau} \sim 25eV$
- COLD
  - WIMPS/Inos $\sim 100GeV$
  - Axions $\sim 10^{-5}eV$
  - Planetary Mass Black Holes

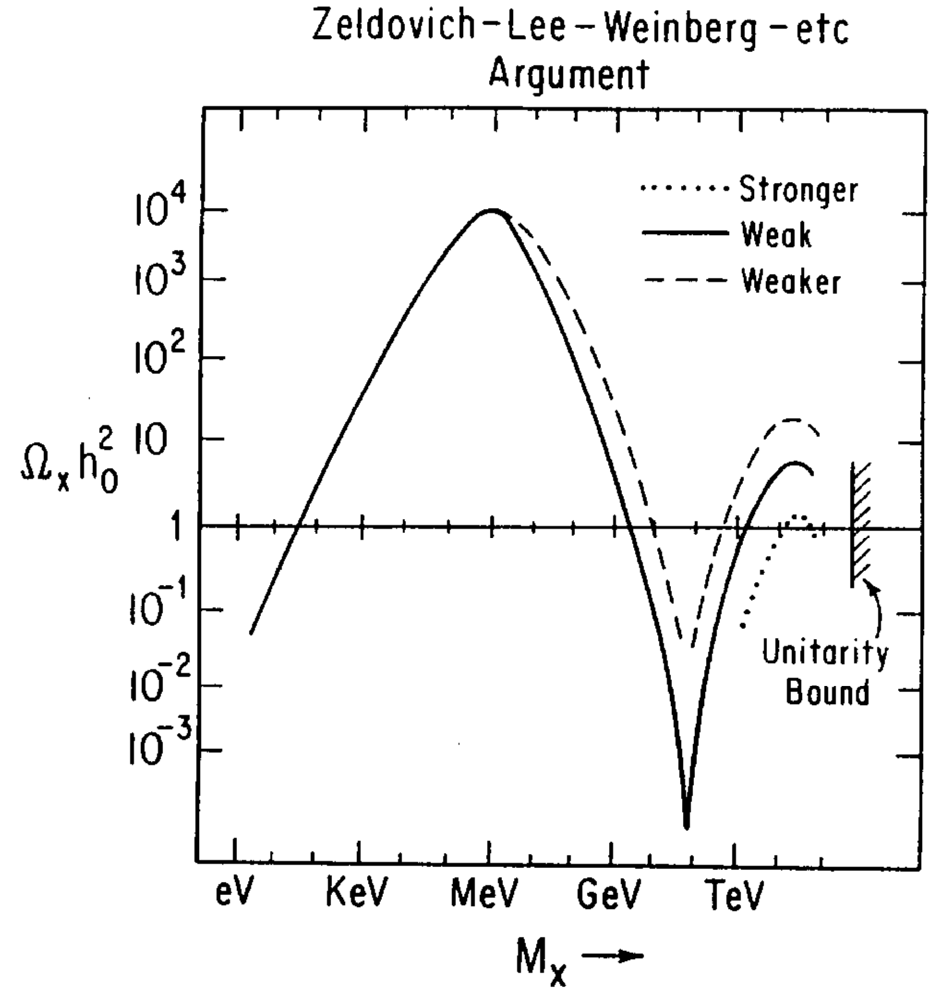

Figure 3 $\Omega_x h_0^2$ versus M_x for weakly interacting particles showing three or more crossings of $\Omega h_0^2 = 1$. Note also how the curve shifts at high M_x for interactions weaker or stronger than normal weak interaction (where normal weak is that of neutrino coupling through Z^o). Extreme strong couplings reach a unitarity limit at $M_x \sim 340 TeV$.

A new potential argument which may favor CDM-WIMPS (but not axions nor any HDM candidate) has been put forth by David Dearborn (private communication). In particular, WIMPs of mass greater than several GeV will be captured and collected by globular cluster stars. Their motion will affect energy transport if M $\lesssim$ 20 GeV. This alternate energy transport would enable a globular cluster to appear several Gyr older than it actually is. Thus, if high Hubble constants are ever confirmed, these WIMPS could eliminate the contraditction between low Hubble ages and apparently high globular cluster ages.

A few years ago the favorite dark matter candidate was probably a few GeV mass WIMP. However, the lack of discovery of any new particles in the high energy collider experiments now means that the favored massive particles to serve as CDM lean towards masses greater than about 20GeV and interactions weaker than that of a neutrino[19] (see Figure 4). However, models can still be constructed which avoid the LEP and CDF bounds and yield WIMPS of sevêral GeV. It is curious but not damning that those models were not particularly popular prior to the tightening of the accelerator bounds.

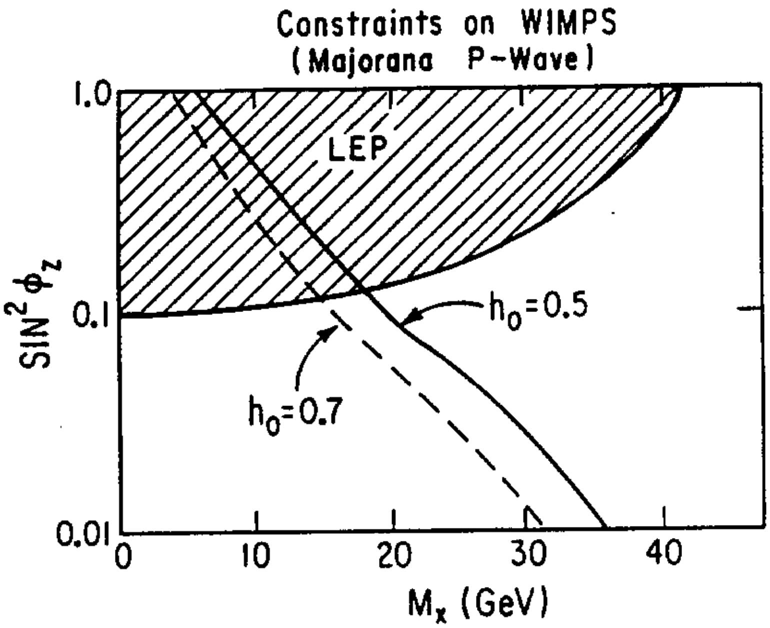

Figure 4a. Constraints on WIMPs of Mass M_x versus $\sin^2\theta_z$ that yield $\Omega = 1$. the cross-hatched region is what is ruled out by the current LEP results. Note that $\Omega = 1$ with $H_o = 0.5$ is possible only if $M_x \lesssim 20$ GeV and $\sin^2\theta_z < 0.1$.

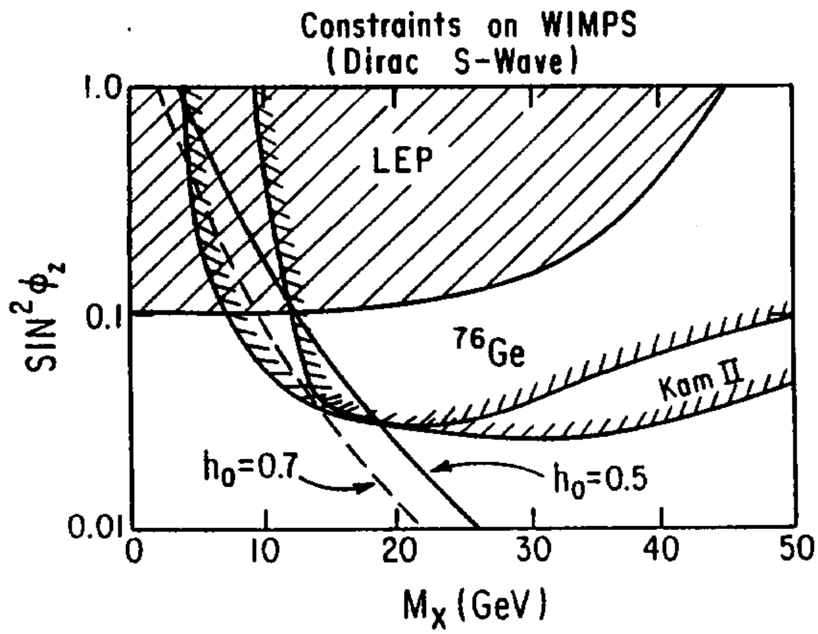

Figure 4b. This is the same as 4a but for Dirac particles (s-wave interactions). The ^{76}Ge region is that ruled out by the Caldwell *et al.* double-β style experiments. This figure is revised from that of Ref. 17 using latest LEP results and using new Kamiokande limits which closed a possible loophole near $M_x \sim 10$GeV. The current results require $M_x \gtrsim 20$ GeV and $\sin^2\theta_x \lesssim 0.03$ for matter-antimatter symmetric particles and also exclude the entire cross-hatched region for asymmetric particle candidates.

While discussing dark matter candidates, it is worth noting that recent hints from new solar neutrino observations suggest that neutrinos may indeed have small masses.[20] Although the mass directly implied ($m_{\nu_\mu} \sim 10^{-2}$ to $10^{-3.5}$ eV) is too small to yield Ω of unity, reasonable "see-saw" scaling

$$m_{\nu_\tau} \sim m_{\nu_\mu}(\frac{m_{top}}{m_c})^2$$

of the results to the less constrained tau neutrino would put its mass in the range where it could yield Ω of unity. This has created a renewed interest in HDM models.

SEEDS FOR MAKING STRUCTURE

In addition to matter, all models for making galaxies and larger structures require some sort of "seeds" to stimulate the matter to clump. The seeds can be divided into two generic categories:

(a) Gaussian Density Fluctuations; and

(b) Topological Defects (cosmic strings, walls, textures, etc.).

Both gaussian density fluctuations and topological defects are assumed to be generated by some sort of vacuum phase transition in the early universe. Proposed transitions are associated with spontaneous symmetry breaking of unified forces. For example, the Grand Unified (GUT) transition can, in principle, create both types of seeds when the universe was at a temperature of about 10^{28}K. Recently, it has also been proposed that a cosmological phase transition may occur as late as a temperature of ~100K (after the decoupling of the cosmic background radiation) and also be able to generate either type of seed.[21]

It is interesting to realize that <u>all</u> models for generating structure in the universe require some new fundamental physics, both in the form of exotic matter and some vacuum phase transition to produce seeds. Thus, the study of the structure of the universe should teach us new physics as well as astronomy.

For readers who remember the discussions of seeds and structure formation of twenty years ago, it is useful to put the current ideas into the former framework.[22] Prior to the introduction of Grand Unified or microphysics models for generating fluctuations, one merely noted that density fluctuations in matter could be divided into two general classes:

1) adiabatic;

and

2) "isocurvature" (or almost equivalently "isothermal", since in the early universe $\rho_b \ll \rho_r$).

In the adiabatic case, the ratio of baryon density, n_b, to radiation density, n_γ, is unchanging, so any variation in n_b is accompanied by a variation in n_γ. In the isothermal case, n_γ remains fixed, so only n_b varies, and in the isocurvature case, the total energy density (which yields cosmic curvature) is fixed so that variations in the energy density are accompanied by opposite compensating variations in the energy density of photons, ρ_γ. But since $\rho_\gamma \gg \rho_b$, the variations in ρ_b don't really affect ρ_γ, so isocurvature behaves just like isothermal.

With the development of grand unified models and particularly the realization that baryons were probably produced by some variant of the Sakharov process,[23] it was noted[24] that adiabatic fluctuations were preferred for baryon density fluctuations. If baryons are generated by temperature-dependent microphysics processes, then a constant isothermal temperature everywhere would result in the same baryon density everywhere and yield no baryon density fluctation. A way around this would be to have the "seed" not be a matter density fluctuation itself, but, instead, be some separate physical seed which is the function of a topological defect. Such a defect does not alter the thermal background, so in the old classification it is isothermal or isocurvature. However, topological seeds do not yield gaussian distribution, but, instead, are patterns. Thus, if one wishes to use the old language, the gaussian quantum seeds are the old gaussian adiabatic fluctuations and topological seeds are the old isothermal/isocurvature seeds with the added constraint of being non-gaussian. The key new point is that these models are motivated by fundamental physics ideas rather than just mathematical formalism.

Figure 5 shows how density fluctuations grow as the universe expands. If the seed is produced by a phase transition prior to the decoupling of the CBR, then the observed isotropy of that radiation constrains the initial fluctuation amplitude to be quite small and small fluctuations grow slowly, as indicated. (Note that the constraints on density fluctuations from the CBR are relaxed from that shown in Figure 5 if the seeds are non-gaussian topological defects.) Such a slow growth means that the bulk of the objects form relatively late when the average fluctuation size is comparable to the average density itself. This slow growth is a serious constraint on such models and is one of the motivations behind recent models with a late phase transition occurring after the decoupling of the background radiation. In this latter case, the growth can be much faster without violating the isotropy limits.

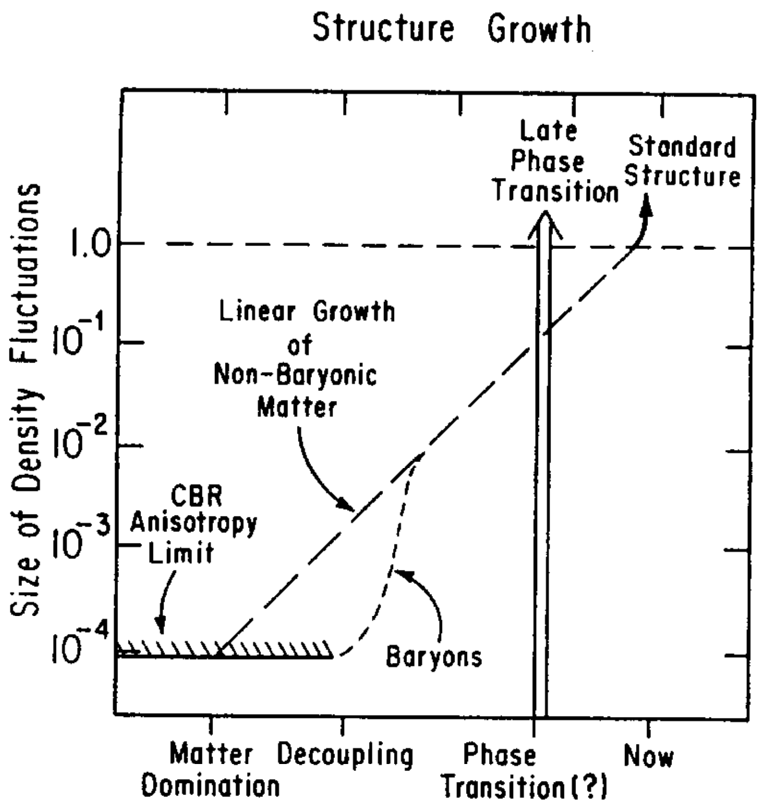

Figure 5. Linear growth of $\delta\rho/\rho$ versus inverse temperature with epochs noted.

The favorite structure formation model until recently has been a combination of (1) gaussian density fluctuations with a spectrum of equal amplitude on all scales as might be expected from quantum fluctuations at the end of inflation (see discussion in reference 25), and (2) CDM. Although the model is known simply as the "cold dark matter model," it is important to remember that a critical (and perhaps fatal) part of this model is actually its assumption about the nature of the seeds. (The model also requires something known as "biasing" so that only a small fraction of the baryons ends up in shining regions). The alternative of random density fluctuations with HDM fails because it doesn't produce "small" objects like galaxies fast enough (although Melott[26] and his colleagues argue that this point is debatable). We will see that a similar problem may eventually occur for the CDM model, given the recent observations of large numbers of high redshift objects. However, HDM (and CDM) can avoid this problem if the seeds are topological (or if there is a late-time phase transition).

LARGE-SCALE STRUCTURE OBSERVATIONS

Let us now turn to the actual large-scale structure observations which, we hope, will select among the different models. (It is worth noting that other than for these recent large-scale structure observations, the CDM model with random fluctuation seeds has done a remarkably good job of explaining most extragalactic observations, including the basic observed properties of individual galaxies. Even bizarre "cosmologies" which fail to fit the 3K background or light element abundances and are designed in an *ad hoc* way to make galaxies [the so-called "plasma cosmology" comes to mind] don't do as good a job as the CDM model in this regard.)

The key recent observations pertain to the following:

(1) cosmic background isotropy;
(2) quasars found at large redshifts;
(3) large coherent velocity flows;
(4) structures with scales of $\gtrsim 100Mpc$;
(5) large correlations of clusters of galaxies.

The first one of these we've already noted on Figure 5. While the present limits marginally allow structures to form by the present epoch, it is clear that if the limit gets pushed down much further, no model with gaussian primordial density fluctuations will survive.[27] The current temperature variation limits when observing in different directions are at the level of a couple parts in 10^5 (which translates into the density fluctuation limits shown in Figure 5). The Cosmic Background Explorer (COBE) satellite expects to push the limit down to about 5 parts in a million. Furthermore, independent cosmic radiation studies to be carried out at the South Pole by a Chicago-Princeton team and by a University of California team expect eventually to push the limit down to a single part in a million. This should either see something or force us to a late generation of seeds.

Pushing the opposite direction on the "zone of mystery" epoch between the background radiation and the existence of objects at high redshift is the discovery of objects at higher and higher redshift. The higher the redshift of objects found, the harder it is to have the slow growth of Figure 5 explain their existence. Some high redshift objects can be dismissed as statistical fluctuations if the bulk of objects still formed late. In the last year, the number of quasars with redshifts > 4 has gone to 30, with one having a redshift[28] as large as 4.9. Furthermore, there appears to be no significant intergalactic gas near these quasars. Thus, either the bulk of the gas has already been incorporated into objects (contrary to the slow growth picture) or the gas has somehow been heated and/or kept hot enough to be ionized (but not so hot as to emit x-rays). While such constraints are not yet a serious problem for linear growth models,[29] eventually they might be.

The large velocity flows have already been discussed with regard to the implication of $\Omega = 1$ on scales of $\sim$ 100 Mpc. To generate structures as large as the Great Attractor and the associated high velocity flows on those scales can be a problem since it tends to require large amplitude fluctuations if the seeds are gaussian fluctuations.[27] (Non-gaussian topological defects may not be as severly constrained since simple rms $\Delta T/T$ averages are not appropriate.)

The large-scale observations which have gotten the most publicity recently are the direct maps of the large structures in the universe.[30] In particular, note that their maps show objects such as the "Great Wall" which stretch for over 100 Mpc. Furthermore, the deep pencil beam surveys of Kron, Broadhurst, Ellis, Koo and Szalay[31] (see Figure 6) show that the great walls appear to be ubiquitous in the universe and may have a quasi-regular spacing of about 100 Mpc. Thus, again we see indications of significant structure on scales of about 100 Mpc.

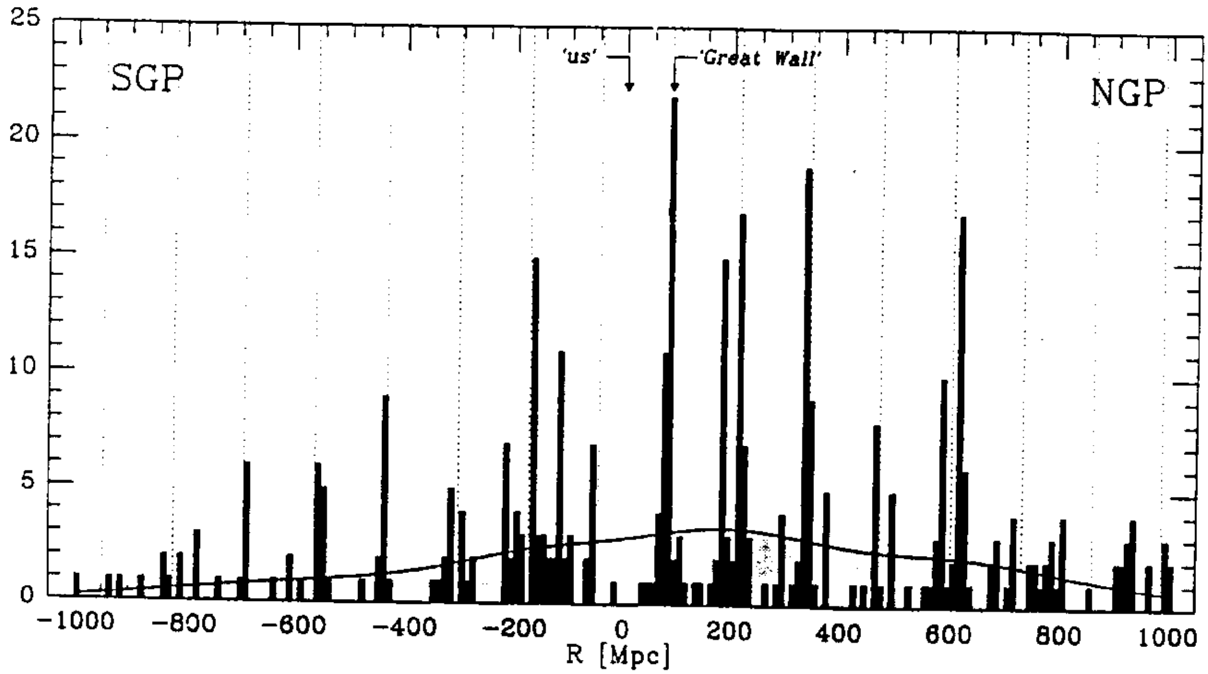

Figure 6. Galaxy counts versus distance from the combined pencil beam surveys of Koo, Kron and Szalay for the North Galactic Pole (NGP) and Broadhurst and Ellis for the South Galactic Pole (SGP).

While these maps certainly show us large-scale structure in a graphic way, the question up until last year had been "what's the statistical significance?" In other words, could these big things be relatively rare statistical flukes or are they common? Random seed models with CDM and a spectrum that has equal size fluctuations on all scales can give occasional large structures, but was there more "power" on large scales than such a spectrum could yield. The answer to this latter question has come from some new large surveys of galaxy positions. In particular, the Automatic Plate Measuring (APM) survey headed by Efstathiou of Oxford and the Queen Mary-Durham-Oxford-Toronto (QDOT) survey of IRAS galaxies[32] and the 2nd Palomar sky survey (POSS II) analysis of Picard[33] of Caltech all now have statistically significant samples that show that indeed there is more power on large scales than can be accomodated by the seed spectrum assumed in the so-called CDM model (see Figure 7). Note that it is the seed part of the model that is having difficulties, not the matter itself.

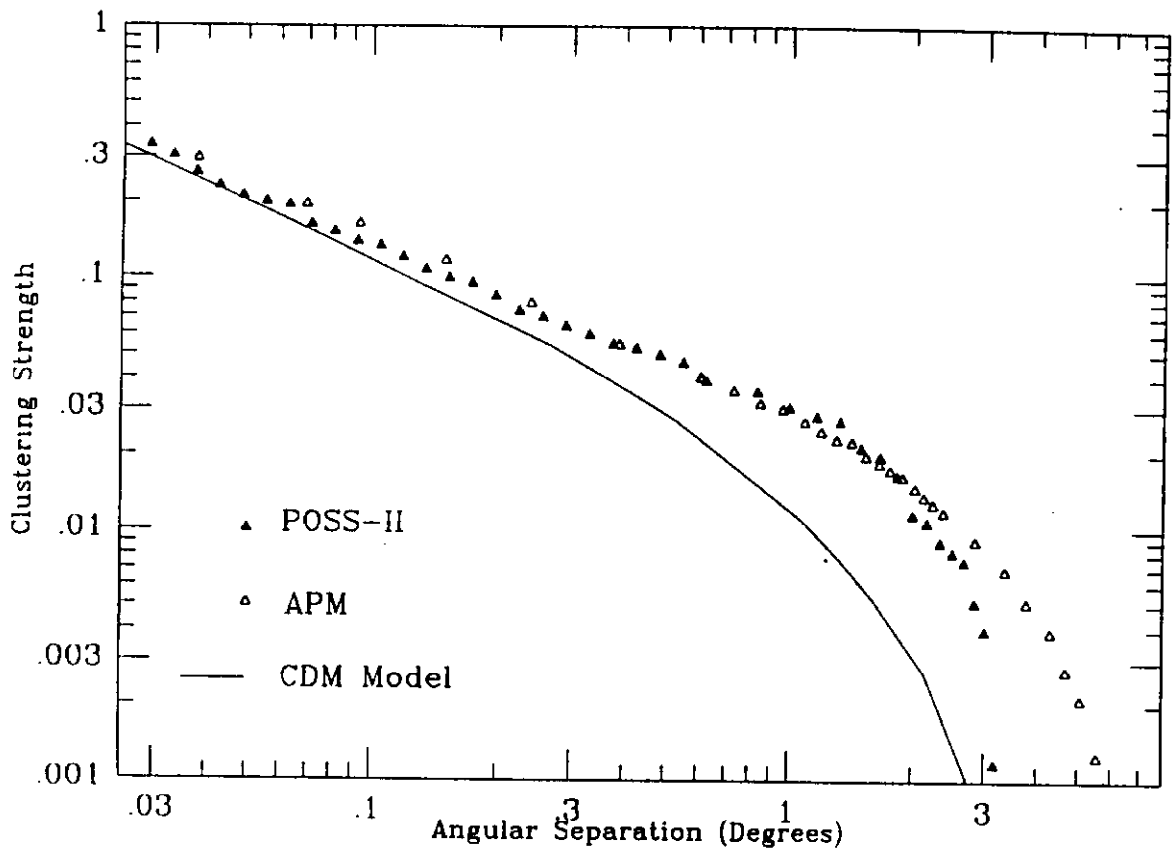

Figure 7. The galaxy-galaxy correlation function versus angular separation. The solid line is the flat gaussian density fluctuation distribution utilized in the so-called cold dark matter models.

Of course, a complete, statistically significant mapping out of the structures requires the three dimensional positions of far more galaxies than any of the current surveys provide (currently $\sim$ 10,000 at most). The University of Chicago, Princeton University, the Institute for Advanced Study and Fermilab are now building a dedicated telescope which will get the three dimensional positions of a million galaxies and thus, to some extent, fill in the pencil beams to see how regular the structures really are.

The last large-scale structure item to be discussed is the apparent predilection that clusters of galaxies have to be near each other rather than randomly distributed. Bahcall and Soneira[34] reported that it is more likely for a cluster to be near another cluster than for a galaxy to be near another galaxy. If gravity alone is responsible for the grouping, this sounds backwards. The average density of galaxies is higher and the distance to move is smaller to obtain clumping. Thus, if gravity alone were at play, then clusters should not be so strongly correlated with each other. At first, people tried to get around this point by arguing that projection effects might explain it. However, recent work[35,36] has shown that the centers of these clusters do seem strongly correlated. Efstathiou *et al.*,[37] using the APM data, do not find as strong a correlation as Bahcall and Soneira, although they still seem to find more power on large scales than a flat, gaussian seed spectrum would give. Complete resolution will require the new million-galaxy surveys or with cluster correlations using clusters identified by their x-ray emission from the ROSAT and AXAF satellites. If correlations are stronger than random, then we would have to conclude that galaxies and clusters do not form from just random seeds and gravity but, instead, the seeds are laid out in some pattern.[38] A pattern is exactly what topological defect models tend to predict.

Figure 8 shows the Szalay-Schramm dimensionless correlation strength β versus the average separation of catalog objects for all of the recent cluster catalogs. The new data continue to support the earlier[38] conjecture that cluster correlations are scale-free. Similarly, the galaxy-galaxy correlation continues to be high on this scale-free plot, as one might expect if gravity enhanced the galaxy correlations relative to an underlying fractal seed structure. The new cluster-cluster β is ~ 0.26 compared to the earlier estimate of ~ 0.35. Thus, as Efstathiou *et al.*[37] emphasize, the clustering amplitude is a bit smaller, but as Bahcall[36] emphasizes, the scale-free nature up to ~ 100 Mpc does persist. It is important to note that this fractal-like behavior probably does not extend to scales $\gg$ 100 Mpc. As Luo and Schramm[39] emphasize, the horizon mass at the time of galaxy and structure formation is probably a limit on the maximum fractal formed. This is supported by the smoothness of the microwave background on scales larger than the horizon at recombination.

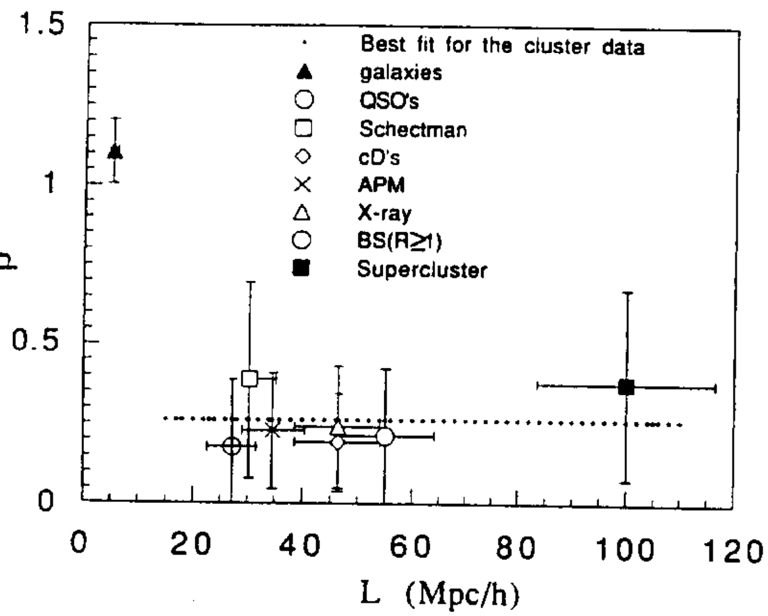

Figure 8. The Szalay-Schramm[37] dimensionless correlation strength β versus the average spacing of catalogue samples, L. Note the apparant scale-free nature of cluster-cluster correlations. The figure is from Luo and Schramm.[38] The Bahcall-Soniera (BS) data is from reference 33, the cD data from reference 34, the APM data from reference 36 and the other data from reference 35.

CONCLUSION

Galaxy and structure formation is obviously a very active field. By necessity, the models work in the Big Bang framework. The details for the models all invoke new fundamental physics, both for the generation of seeds and for the non-baryonic dark matter. Which new physics is right remains to be seen. The model with CDM and random seeds was the front runner, but it is running into problems with the new large-scale structure observations. However, variants on this model, putting larger amplitude fluctuations on large scales, may still survive if the fluctuations get truncated on still larger scales to avoid microwave anisotropy constraints. Other models with late phase transitions generating the seeds or with topological defects as seeds are also looking quite attractive. These latter models may work with either HDM or CDM (although HDM may be preferable as it provides a natural biasing mechanism).

Fortunately, in the near future, a battery of experiments and observations will be carried out which should resolve the problem. In addition to the million galaxy maps, the improved CBR limits and the x-ray satellite observations, we will also profit by the new large ground telescopes and HST observations of galaxies near the time of their formation. Furthermore, new dedicated telescopes are being developed to search for dark baryonic matter in the Galactic Halo, using gravitational microlensing techniques. (It is interesting that more and more dedicated rather than general purpose telescopes are the direction being taken for cosmological problems). But cosmology is no longer tackled with telescopes alone. Experimental particle physicists have also gotten in the game. Direct search experiments are being built to try to detect WIMPS and axions. Also, new accelerator experiments, including the SSC and LHC, will put new, tighter constraints on WIMPS, and mixing experiments at Fermilab and/or CERN may find the mass of the tau neturino through its mixing with other neutrinos. Many of these questions should be resolved before the end of the decade.

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